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14. ABSTRACT
Power efficiency issues are investigated across layers for use in tactical communications among battery-operated wireless sensor networks (WSNs) and wireless MANET nodes. Fundamental limits, practical guidelines, specific algorithms at the physical, data link, and application layers as well as performance analysis of tactical networks are developed when power optimization (as opposed to, e.g., throughput or delay, pursued by existing approaches) is the ultimate goal. Challenges addressed include the harsh interference environment, along with the stringent power

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Wireless sensor networks, consensus-based distributed estimation and tracking, quantization noise, interference, cross-layer designs, congestion and contention control, pulse position modulation (PPM), frequency shift keying (FSK), battery power efficiency, fading

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PI: Georgios B. Giannakis (U. of Minnesota), August 14, 2009

Statement of the problem studied: The overarching goal of this research has been to investigate thoroughly power efficiency issues across layers for use in tactical communications among battery-operated wireless sensor networks (WSNs) and wireless MANET nodes.

Novelty: The innovative approaches developed in this project pertain to fundamental limits, practical guidelines, specific algorithms at the physical, data link, and application layers as well as performance analysis of tactical networks when power optimization (as opposed to e.g., throughput or delay pursued by existing approaches) is the ultimate goal.

Scientific barriers: The challenges to overcome include coping with the harsh propagation environment, fading, and (non-) intentional interference present in the battlefield along with the stringent power and bandwidth constraints that low-cost sensors are envisioned to operate with.

Accomplishments/Results: Findings and highlights of the research performed under this project are summarized in the next page along the following five themes:

(a) Battery Power-Efficient Non-Coherent Modulations for Wireless Sensor Networks
(b) Power-Optimizing Adaptive Transmitter Design for Coherent Sensor Communications
(c) Fundamental Limits for Power-Efficient TDM/OFDM Scheduling
(d) Power-Constrained Optimal Quantization for Tactical Wireless Sensor Fusion
(e) Distributed Parameter Estimators and Trackers via Wireless Sensor Networks
(f) Power-Efficient Resource Allocation in Wireless Relay Transmissions
(g) Power-Efficient Scheduling for Wireless Sensor Networks
(h) Power-Efficient Wideband Communication with Limited Rate Feedback
(i) Cross-Layer Congestion and Contention Control for Wireless Ad Hoc Networks

Highlights are also provided in the slides attached. Detailed exposition of the accomplishments can be found in the journal papers of this final report.

Significance to US Army: Development of low-cost sensors, robust waveform designs for inter-sensor communications, power-efficient scheduling and resource allocation protocols for sensor networks with prolonged battery lifetime is of paramount importance for tactical WSNs deployed for monitoring, surveillance, decentralized detection, estimation and tracking tasks.

Collaborations and levered funding: Results from this project leverage nicely the PI's research with Army Research Laboratory (ARL) Personnel (Drs. A. Swami and B. Sadler) under the Collaborative Technology Alliance on Communications and Networking (CTA on C&N). Specifically, the battery-efficient non-coherent Tx-modules with optimal number of quantization bits developed under this ARO project can be utilized for power-efficient stochastic routing and anti-jam relay MIMO communications investigated under the ARL-CTA project.

Technology transfer: As with byproduct research performed under the ARL-CTA, we expect that the power-efficient waveform designs and resource allocation policies developed under this grant will be tested by CERDEC for possible incorporation in the evolution of JTRS modules and tactical wireless sensor networks. Matlab codes implementing these modules were sent to CERDEC personnel in May 2007.

Accomplishments/results:

A. Battery Power-Efficient Non-Coherent Modulations for Wireless Sensor Networks

Our first thrust pursued power issues at the battery level (lower part of the physical layer). As sensor nodes are typically powered by non-renewable batteries, power efficiency is a critical factor especially for tactical wireless sensor networks (WSNs). Orthogonal modulations appropriate for resource-limited WSNs have been investigated under the assumption that batteries are linear and ideal, but their effectiveness is not guaranteed when more realistic nonlinear battery models are considered.

We introduced a general approach that integrates typical WSN transmission and reception modules with realistic battery models and developed two battery power-conserving schemes for M-ary orthogonal modulations that are encountered in tactical communication systems, namely pulse position modulation (PPM) and frequency shift keying (FSK), both tailored for WSNs. We specifically considered a fully-functioning sensor node, where the battery power consumption is closely related to the transmit power, the analog circuit power consumption during transmission and reception modes and the battery non-linearity. We further analyzed and compared the battery power efficiency of PPM and FSK over path-loss and fading wireless channel models.

We revealed interesting properties of PPM and FSK with respect to battery power efficiency, dependence on the density of the sensor nodes deployed, modulation constellation size and the type of the wireless channel. Specifically, in sparse WSNs with negligible circuit power consumption, FSK turns out to have power efficiency advantage over PPM for all constellations of any size M and transmitter-receiver distance d in path-loss and fading channels; the advantage in fading channels is greater than that in path-loss channels but no more than 3 dB. However, when transmission distance decreases and the circuit power consumption is comparable to the transmit-power, PPM and FSK have their respective advantage regions: PPM is more power efficient at relatively higher data rates and/or denser sensor deployments; and the advantage of PPM over FSK in path-loss channels is greater than that in fading channels. In very dense WSNs, when circuit power consumption dominates the total power consumption of sensors, PPM outperforms FSK over all M and exhibits huge power gains that increase with M.

B. Power-Optimal Adaptive Transmitter Design for Coherent Wireless Sensor Communications

In this thrust, we exploited quantized channel state information (Q-CSI) provided in the form of a few feedback bits from the receiver to the transmitter in order to adapt the transmit-waveform so that power is minimized. The setup entails battery-operated sensors communicating with a fusion center (FC) using adaptive modulation and coding over a wireless fading channel.

By viewing the coherent WSN setup as a distributed space-time multi-input single-output system, we first developed optimal distributed beamforming and resource allocation strategies to benchmark performance when perfect (P) CSI is available the full (F-) CSI is available. We further developed optimal adaptive transmission policies and designed optimal channel quantizers for the finite-rate feedback case where the sensors only have Q-CSI, or, each sensor has P-CSI of its own link with the FC but only Q-CSI of other sensors. Thorough simulations confirmed that that our novel finite-rate feedback based strategies attain power efficiency surprisingly close to the optimal P-CSI based benchmark. They outperform markedly a statistical (S) CSI based scheme which only exploits spatial diversity with P-CSI, and offer significant power savings relative to open loop systems that do not exploit CSI.

C. Fundamental Limits for Power-Efficient TDM/OFDM Scheduling

Having optimized point-point power efficiency, we moved on to multi-access orthogonal signaling schemes to optimize scheduling and allocation of resources so that the overall average power of the network is minimized. Such policies were investigated for both time division multiple access (TDMA) and orthogonal frequency division multiple access (OFDMA) over fading channels in the power-limited regime. For frequency-flat block-fading channels and transmitters having full, i.e., P-CSI we first minimized power under a weighted sum average rate constraint and showed that the optimal rate and time allocation policies can be obtained by a greedy water-filling approach with linear complexity in the number of nodes. Subsequently, we pursued power minimization under individual average rate constraints and established that the optimal resource allocation also amounts to a greedy water-filling solution. Our novel approaches not only provide fundamental power limits when each node can support an infinite-size capacity-achieving codebook (continuous rates), but also yield guidelines for practical designs where nodes can only support a finite set of adaptive modulation and coding modes (discrete rates).
Another interesting feature of the novel power-efficient resource allocation strategies is that the gateway node/fusion center (which naturally has full CSI) is the one determining the time allocation and feeding it back to nodes. It turns out that the nodes only need their own CSI to determine the optimum transmission rate. In a time-division duplexing mode, the nodes can even obtain their own CSI without feedback from the fusion center since CSI at the transmitters can be acquired via training over the reciprocal channels. Together with the fact that the fusion center needs only a few bits to indicate the time allocation (since the optimal policy is a winner-takes-all one), this feature is attractive from a practical implementation viewpoint.

D. Power-Constrained Optimal Quantization for Tactical Wireless Sensor Fusion

To further effect power savings in a WSN application-specific context (distributed parameter estimation), we developed quantizers under strict power constraints to enable optimal reconstruction at the fusion center. Propagation, modulation, as well as transmitter and receiver structures were jointly accounted for using a binary symmetric channel model. We first optimized quantization for reconstructing a single sensor's measurement, and derived the optimal number of quantization levels as well as the optimal power allocation across bits. The constraints take into account not only the transmission energy but also the power consumed by the transceiver's circuitry. Furthermore, we considered multiple sensors collaborating to estimate a deterministic parameter in noise. In this setup too optimum power allocation and the optimum number of quantization bits were obtained and tested with simulated examples. Finally, we accessed the effect of channel coding on the reconstruction performance under strict power constraints and jointly optimized the number of quantization levels as well as the number of channel uses.

E. Distributed Parameter Estimators and Trackers via Wireless Sensor Networks

To obviate the vulnerability of fusion center (FC) based tactical WSNs to jamming, we also pursued fully distributed *in-network* schemes for decentralized estimation and tracking, whereby each sensor communicates only with its neighbors, and the estimation task is performed in a totally distributed fashion. Our novel decentralized schemes: i) guarantee that sensors obtain the desired estimates; ii) rely only on single-hop communications; and iii) exhibit resilience when inter-sensor communication channels are noisy and jamming causes link failures.

Our approach is based on successive refinements of local estimates maintained at individual sensors. The resultant iterative algorithms comprise a communication step where the sensors

interchange information with their neighbors, and an update step where each sensor uses this information to refine its local estimate. Iterations proceed until all sensors consent on the estimated value of the parameter or dynamical process of interest; hence the term consensus-based estimation. Our novel approach formulates the desired estimator as the solution of convex minimization sub-problems that exhibit a separable structure and are thus amenable to *distributed* implementation. Different from existing alternatives, our framework leads to decentralized estimation algorithms even when the desired estimator in not available in closed-form, as is frequently the case with maximum-likelihood and maximum a posteriori estimation. We further established that the resultant algorithms exhibit robustness to interference and noise.

We finally extended our distributed framework and developed decentralized estimation schemes with correlated observations even for random signals. Specifically, we developed algorithms for optimal estimation of stationary random parameters and smoothing of (even nonstationary) dynamical processes based on generally correlated observations collected by ad hoc WSNs. For decentralized tracking applications, distributed Kalman filtering and smoothing algorithms were obtained for any-time mean-square error (MSE) optimal consensus-based state estimation. The novel distributed smoother is flexible to trade-off estimation delay for MSE reduction, while it exhibits resilience to interference and noise. Analysis and corroborating simulations demonstrated the merits of the novel distributed estimators in the context of distributed target tracking.

F. Power-efficent resource allocation in wireless relay transmissions

In recent years, relay transmissions have attracted a lot of attention owing to the emergence of wireless ad hoc links as a flexible network architecture capable of supporting many different applications such as data networks, home networks and sensor networks. Unlike cellular networks and most WLANs, where nodes communicate through a central node linked to a wired backbone, in wireless ad hoc networks, communication between different nodes relies on intermediate nodes acting as relays. Since, in many wireless ad hoc networks, the reliance on battery makes power a premium, it is of interest to study performance of relay transmissions in the low-power regime.

We studied the energy required for transmitting one information bit under three different relay schemes: amplify and forward (AnF), decode and forward (DnF), and block Markov coding (BMC). Two different scenarios one may encounter in practice have been considered. In the first scenario, the relay has access to a fixed power source, and hence theoretically unlimited power supply. For these applications, analysis and simulation indicate that: i) AnF achieves the best energy per bit at the wideband limit; ii) BMC is always at least as energy-efficient as DnF; and iii) AnF is most efficient when the spectral efficiency is low or when the relay-destination distance is small; otherwise, BMC offers the best energy efficiency. In the second scenario, the relay relies on battery with limited power, and hence its power consumption must also be taken into account. For this class of applications, we demonstrated that: i) BMC always has the same or better energy efficiency than DnF; ii) the energy efficiency of AnF can be substantially improved using bursty transmission in the power-limited regime; and iii) when the relay-destination distance is small, AnF with bursty transmission offers the best energy efficiency, otherwise, BMC and DnF are more energy-efficient.

G. Power-Efficient Scheduling for Wireless Sensor Networks

A wireless sensor network (WSN) typically consists of a large number of sensor nodes distributed over a certain region. Each node monitors its surrounding area, gathers application-specific information, and transmits the collected data to a ``master'' node (a.k.a. fusion center or gateway). Compared with using a single powerful sensor to monitor a large area, a sensor network with a

large number of nodes of limited ability is more robust and may provide a more accurate picture of the monitored area. In WSN, a sensor node may need to operate for long periods of time relying on a tiny battery. It is therefore important to optimize the energy efficiency of all sensor operations, which include sensing, computation and communication. This calls for designing communication protocols that are energy-efficient in the sense of requiring low-complexity processing and low transmission power.

We considered the problem of minimizing the energy needed for data fusion in a sensor network by varying the transmission times assigned to different sensor nodes. By assigning longer transmission times to sensors experiencing worse channel conditions, we derive an optimal scheduling protocol which is able to save more than 80% of the energy needed by the traditional TDMA protocol. Based on the optimal protocol, we then develop a low-complexity inverse-log scheduling algorithm that achieves near-optimal energy efficiency. It is also shown that this inverse-log scheduling has very low computational complexity and incurs negligible overhead in terms of hardware cost and energy consumption needed for executing the algorithm. For sensor networks with a large number of nodes, we further derive a distributed version of the inverse-log scheduling algorithm that is applicable to networks with a large number of nodes. Under this distributed protocol, each sensor needs only to know its own channel gain with the fusion center and the amount of data in its buffer; hence, the communication overhead required by the centralized protocols is eliminated. Simulations demonstrated that the distributed inverse-log scheduling achieves near-optimal energy efficiency in large-scale networks. To analyze energy consumption performance of the inverse-log algorithm, we further computed its asymptotic energy gain over traditional TDMA. We showed that the energy gain of the proposed algorithm increases as the channel variations among different sensor nodes increase. When the total data rate of a network is high, the energy gain does not depend on the total data rate, but increases as the variation among different nodes' queue lengths becomes larger.

H. Power-Efficient Wideband Communication with Limited Rate Feedback

Orthogonal frequency-division multiplexing (OFDM) has been the *workhorse modulation* for *bandwidth-limited* wireline and wireless transmissions over frequency-selective multipath channels. For instance, OFDM has been adopted by digital subscriber line (DSL) modems, digital audio and video broadcasting (DAB/DVB) standards and wireless local area networks. On the other hand and most recently, there has been a great deal of research devoted to *power-limited* communication systems. Examples include wireless sensor networks wherein a serving mote should last for long time (a few months) on a pair of AA batteries that can not be charged or replaced.

Motivated by these facts, we developed an OFDM-based tactical communication system that guarantees *minimum power/energy consumption* while fulfilling imposed constraints on link quality (bit error rate (BER)) and rate of connectivity. The resulting optimum design comprised both *offline* and *online* phases. Given that feedback rate is limited to B bits per sub-channel, we have proposed a quantized (Q-) CSIT based scheme that provides 2^B-1 quantization thresholds per sub-channel (by exploiting channel statistics while working offline). The interplay between the two design phases is that the online phase capitalizes on the thresholds calculated offline so as to eventually allocate bits and power levels in each sub-channel. Reduced complexity alternatives have also been developed to obtain a suite of Q-CSIT based OFDM transceivers with desirable complexity versus power-consumption tradeoffs. A dramatic reduction in complexity has been achieved by first expressing power levels in terms of quantization thresholds and thus reducing dimensionality (search space). Along with our novel designs with Q-CSIT, we have provided a thorough study of the power-efficient OFDM design by considering power optimization based on

deterministic CSIT (D-CSIT) and statistical CSIT (S-CSIT) for the purpose of completeness as well as comparison with our Q-CSIT based design. We show that our Q-CSIT design exhibits large power gain over S-CSIT design, and the optimum Q-CSIT scheme comes surprisingly close (about 1dB) to the D-CSIT scheme.

I. Cross-Layer Congestion and Contention Control for Wireless Ad Hoc Networks

One of the challenging tasks that a tactical wireless ad hoc network should perform efficiently is congestion control - the mechanism by which the network bandwidth is distributed across multiple end-to-end connections. Its role is to limit the delay and buffer overflow caused by network congestion and provide tradeoffs between efficient and fair allocation of power and bandwidth resources. In wireline networks, congestion control is implemented at the transport layer and is often designed separately from functions of other layers. Since wired links have fixed capacities and are independent, this methodology is well justified and has been studied extensively. In recent years, mathematical models and tools based on convex optimization and control theory have been developed, which cast congestion control algorithms as decentralized primal-dual schemes to solve network utility maximization problems. However, these results do not apply directly to wireless networks because unlike their wireline counterparts, capacities of wireless links are not fixed but dependent on channel conditions as well as the specific medium access control (MAC) protocol used. Since the wireless channel is a shared and thus interference-limited medium, concurrent link transmissions in a local area may fail if interference is very strong. This effect complicates congestion control due to the fact that transport layer flows that do not even share a wireless link in their path can compete if they are located sufficiently close in space. For this reason, a MAC protocol defining rules for orderly or random access to the physical shared medium plays a vital role, and should be optimized jointly with congestion control to ensure efficient utilization and fair sharing of network resources.

In our FY07 research on this topic we investigated a contention-based (namely, random access) MAC and studied joint end-to-end congestion control and per-link contention control over a tactical wireless mobile ad hoc network. Because the original problem is non-convex and coupled, we devised a decoupled and dual-decomposable convex re-formulation, based on which we developed subgradient-based cross-layer algorithms to solve the dual problem in a distributed fashion based on non-logarithmic utilities. The specific approach comprises a set of new variables that can be interpreted as fractions of traffic contributed to each link by sources that use this link and allows generalization of existing approaches from single-hop flows to general multiple-hop end-to-end flows. Using a dual-based approach, we showed that the joint problem can be vertically decomposed to the congestion control sub-problem at the transport layer and the contention control sub-problem at the MAC layer. Our solution enjoys benefits of cross-layer optimization while maintaining the simplicity and modularity of the traditional layered architecture. Finally, the resultant protocol has proven convergence and optimality and nice economic interpretations, paralleling existing interpretations in wireline networks.

Battery Power-Efficient Non-Coherent Modulations for Wireless Sensor Networks

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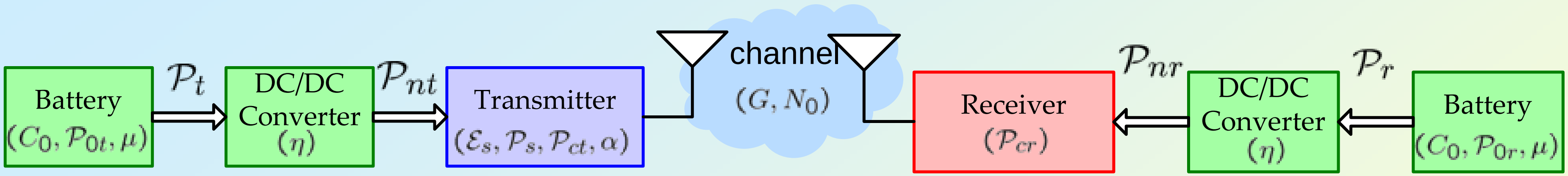


Issues Addressed/Challenges

- Optimized M-FSK and M-PPM to maximize lifetime of non-renewable sensor battery
- Must account for Tx- and circuit-power consumption and battery nonlinearities

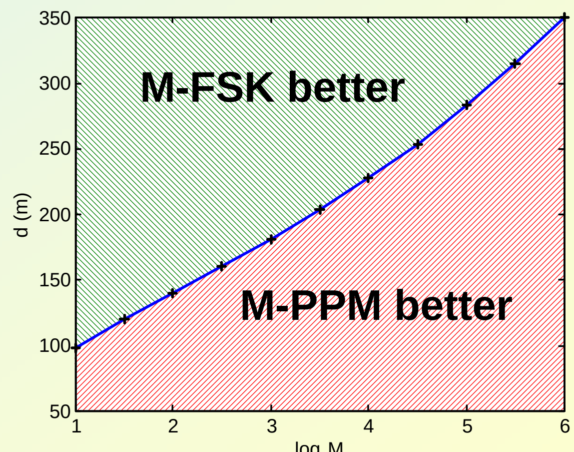
Accomplishments

- **Sparse WSNs**: M-FSK more power-efficient than M-PPM (gains increase with M and average inter-sensor distance (d) up to 3dB)
- **Dense WSNs**: PPM more power-efficient than PPM (gains increase with M)

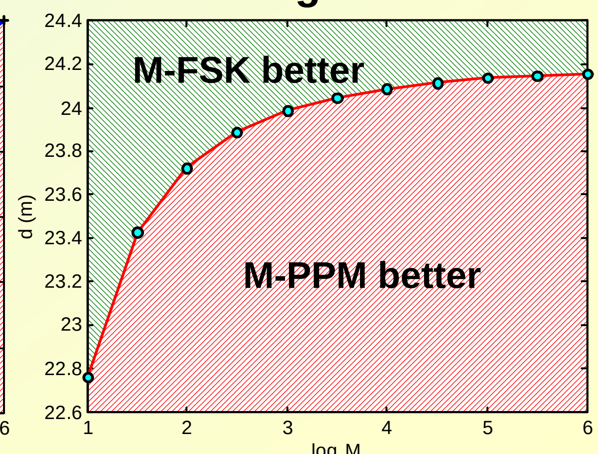
Technical Approaches

- Included circuit consumption, battery parameters (discharge power, DC/DC converter efficiency) along with Tx-Rx power to evaluate bit error rate in non-coherent demodulation
- Analyzed effects of path-loss, fading and density of sensors

Path-loss channel



Fading channel



Power-Optimizing Adaptive Transmitter Design for Coherent Wireless Sensor Communications

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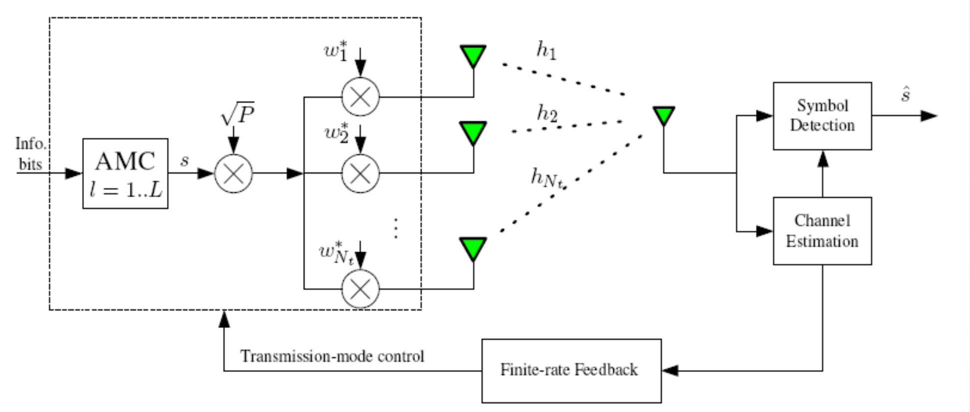


Issues Addressed/Challenges

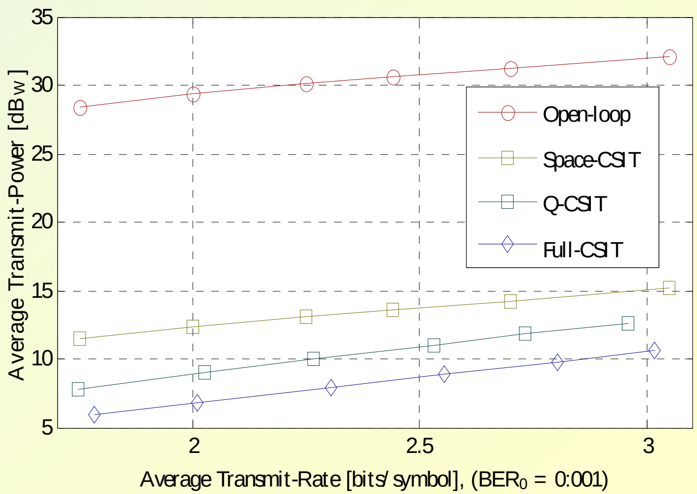
- **Exploit quantized channel state info. (Q-CSI) to save Tx power**
- **Perfect (P) CSI impossible with wireless mobile networks; only a few feedback bits pragmatically available**
- **Sensitivity to synchronization and channel coherence**

Accomplishments

- **Power-efficient Tx adaptation & channel quantization**
- **Huge power savings with 2-3bits of Q-CSI (2dB from benchmark design based on P-CSI)**

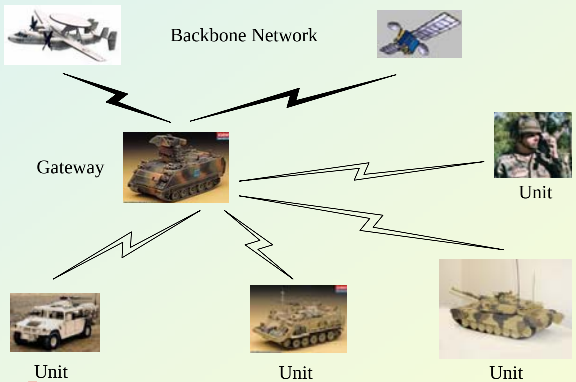
Technical Approaches

- **Minimized average Tx-power under rate and bit error rate requirements**
- **Designed adaptive modulation/coding (AMC) based min-power beamforming**
- **Selected Q-CSI bits using min-power as criterion for channel quantization**



Power-Efficient TDM/OFDM Scheduling for Tactical Communications: Fundamental Limits

G.B. Giannakis, U. of Minnesota



Issues Addressed/Challenges

- Given channel state information (CSI) design scheduling/resource allocation over fading channels to minimize power consumption of wireless nodes under min-rate, delay and error requirements
- Fundamental limits under perfect (P) vs. quantized (Q) CSI with limited feedback
- Battery operated wireless sensors

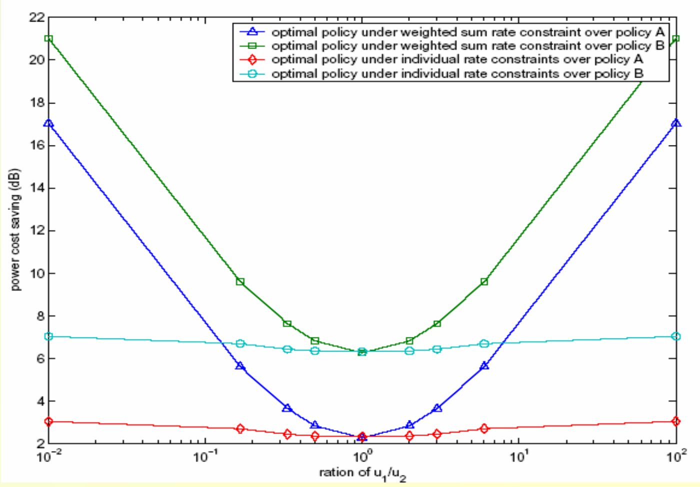
Accomplishments

- Fundamental limits for max. power-efficiency
- Low-complexity policies (linear in # sensors)
- Savings of optimal vs. equal power allocation:

  P-CSI: >20dB; Q-CSI: >6dB w/ 3-bit feedback

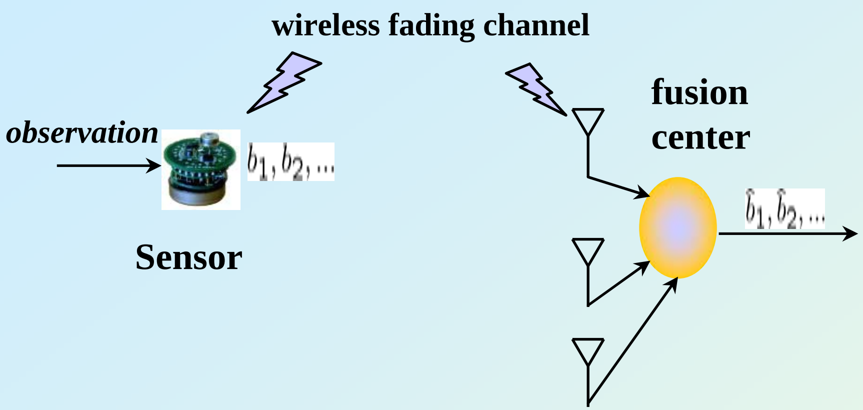
Technical Approaches

- Introduced achievable power region
- Employed primal-dual approach to min. average power subject to average sum-rate and individual rate constraints for TDM/OFDM based access
- Incorporated capacity-achieving rates and adaptive modulation/coding rates



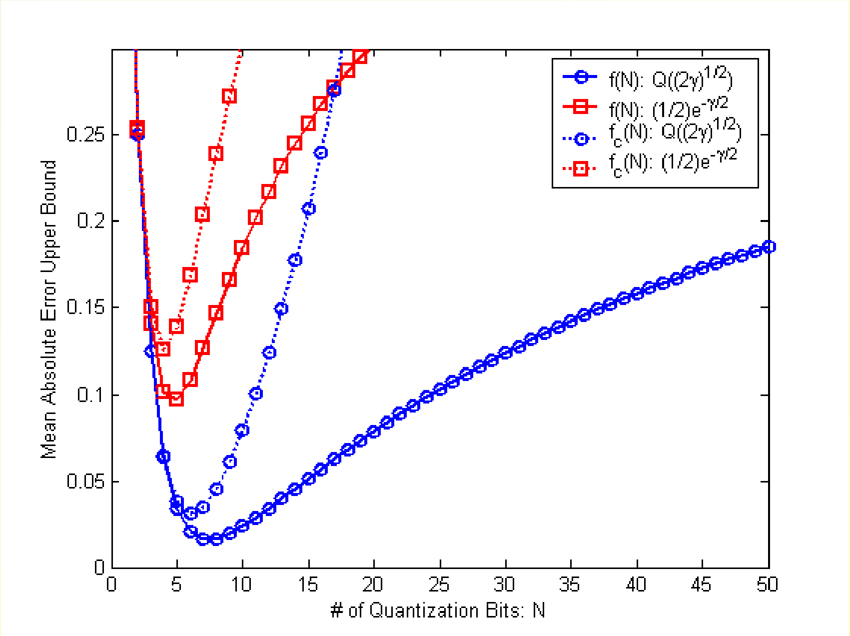
Power-Constrained Optimal Quantization for Tactical Wireless Sensor Fusion

G. B. Giannakis, U. of Minnesota



Accomplishments

- Specified optimum no. of bits per sample for coherent and non-coherent (de-)mod and various fading models
- Allocated optimum no. of quantization/ coding bits and power across sensors



Issues Addressed/Challenges

- Optimize number of quantization bits, power allocation across bits, and coded channel uses to meet power budget per sensor
- Tradeoff: more bits lower reconstruction error but also increase power consumption

Technical Approaches

- Modeled mod-propagation-demod chain as a binary symmetric channel and selected no. of bits and circuit/Tx-power to minimize bound on absolute reconstruction error
- Employed convex optimization to allocate best the available power in sensor fusion

Distributed Parameter Estimators and Trackers via Wireless Sensor Networks

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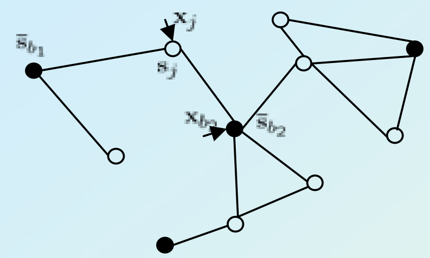

Issues Addressed/Challenges

- Power/bandwidth sensor constraints
- Noisy links and sensor failures
- Low-cost signal estimation and tracking
- Globally optimum distributed schemes in nonlinear, non-Gaussian dynamic setups

Technical Approaches

- Formulation of global estimators/trackers as solution of locally constrained convex optimization problems
- Decentralized algorithms using the method of multipliers combined with a block coordinate descent iteration

Accomplishments

- Noise-resilient distributed estimation/tracking algorithms
- Mean-square error (MSE) optimal dimensionality reduction
- Quantifiable MSE performance